PROPOSED GUIDELINES FOR PROCESSING SIGNALS IN CADAVER TESTING

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INTRODUCTION

The instrumentation and data processing practices most widely followed in impact testing are based on Society of Automotive Engineers recommended practice, SAE-J211. Although this standard was developed primarily for anthropometric test devices (dummies), it is indiscriminately applied to cadaver tests, particularly the dynamic response of data channels used for head acceleration instrumentation. Furthermore, SAE-J211 development is based on the analog signal processing, a well established science which is increasingly being replaced by digital data processing techniques.

The purpose of this presentation is to propose recommended practices to be applied in the following two areas:

1. Frequencies to be filtered out from accelerometer signals used to measure the 3-D rigid body motion of cadaver head, and

2. Processing of biomechanics test signals, including specification of pre-sample filters, and specifications of the dynamic response of digital filters to be applied to the digitized signals.

HEAD ACCELEROMETRY

SAE-J211 specifies that head accelerations in the impact test conform to channel class 1000 specifications. The dynamic response of this channel class requires a flat response (+0.5 dB, -1. dB) up to the cutoff frequency of 1000 Hz; it allows the corner frequency (-3 dB) to be as much as 1650 Hz and requires that the gain rolls off at rate between -9 and -24 dB/octave. This is essentially an analog filter which allows frequencies below 100 Hz to be present in the filtered head acceleration signal.

A careful analysis of the frequency contents of acceleration signals, obtained from 15 cadaver heads direct impacts for the purpose of measuring the head 3-D rigid body motion, reveals that no frequencies higher than 300-400 Hz can reasonably be attributed to pure rigid body motion. Thus, frequencies of 30 ± 2 kHz were ly attributed to resonances of individual accelerometers; 10 ± 3 kHz were attributed to vibrations of the skull structure since they appeared almost simultaneously in all accelerometers; frequencies of 1300 ± 200 Hz appeared in some triaxial signals and not in others, leading us to believe that these were due to resonance in the triaxial mounts; and finally, frequencies between 300-500 Hz were attributed to instrumentation noise.

The question arises then as to the validity of allowing frequencies as high as 1000 Hz to be present in the 9 acceleration signals used to measure the rigid body motion of an impacted cadaver headl i.e., can SAE-J211 be applied to cadaver head rigid body accelerometry? The argument against it is strong, since frequencies not resulting from rigid body motion would introduce artificial components in the calculated six degrees of freedom. If the rigid body assumptions, made when the kinematic equations were written, are to be true, i.e., if the constant distances are to remain constant, then vibrations of the skull and/or the accelerometer mounts must be filtered out. It is therefore recommended that a lower cutoff frequency be applied to head accelerations, when measuring the rigid body motion.

In direct head impacts, the shortest observed duration of the contact force is about 2 msec pulses, which corresponds to approximately 4 msec periods, or a maximum frequency of 250 Hz. The rigid-body response is expected to have the same frequency contents.

To allow rigid body motion measurement of even shorter periods, HSRI proposes the following guideline:

PROPOSAL #1	IN CADAVER HEAD DIRECT IMPACT, SIGNALS FOR RIGID BODY MOTION MEASUREMENTS SHOULD BE FILTERED AT 400 Hz.

In non-impact head motion, resulting from the whole body motion, the rigid-body response pulses are typically 10-30 msec, and in severe cases, some 5 msec pulses (10 msec periods), which corresponds to a maximum frequency of 100 Hz.

To allow even more severe non-impact rigid-body head motion measurements, HSRI proposes the following guideline:

PROPOSAL #2	IN CADAVER HEAD NON-IMPACT, SIGNALS FOR RIGID BODY MOTION MEASUREMENTS SHOULD BE FILTERED AT 200 Hz.

It should be emphasized that these proposed guidelines are to be followed in RIGID BODY motion measurements and should not be used in pressure transducers, strain gages or even accelerometers which are intended to measure local vibratory motions. Finally, it should be pointed out that SAE-J211 does caution against its application in biomechanics instrumentation but does not provide alternatives for such applications.

DIGITAL SIGNAL PROCESSING

The guidelines followed in digital signal processing are primarily derived from the well established analog signal processing. As digital computers became widely available, the convenience of digital processing of the originally analog signal became more attractive.

Initially, digital signal processing was concerned with the ways analog processing could be approximated on digital computers for the purpose of designing and optimizing analog systems before committing them to hardware. As researchers experimented with digital techniques, the science of digital signal processing emerged as an independent field with its own theory and mathematics. However, this new science did not gain wide acceptance until the introduction of the Fast Fourier Transforms, which made the application of digital theory a speedy and economical reality.

Today, biomechanics researchers who process their instrumentation signals on digital computers have to resort to guidelines which were primarily established for electronic equipment. Unless the digital processing principles employed are approximations of analog ones, these guidelines are difficult to follow. An example of these inadequacies is the attenuation of a lowpass filter, given as a rate (dB/octave) for analog filters and their digital approximations, but given as the width of a transition band and the amount of attenuation over this band between the pass and stop bands, for purely digital filters.

In order that the results of biomechanics research in different institutions be uniformly processed, and in order to ensure comparability of these results, it is necessary that guidelines for analog-to-digital conversion and digital filtering be adopted.

ANALOG-TO-DIGITAL CONVERSION

Assuming that the A-D conversion process does not introduce any significant (microseconds) phase shift between channels, and assuming that the resolution is acceptable, the most important variable is the sampling rate and the associated pre-sample anti-aliasing analog filters.

SAE-J211b recommends a sampling rate at least five (5) times the -3 dB frequency of the anti-aliasing filters. Thus, if these analog filters are channel class 1000, the minimum recommended sampling rate is 5 times the 1650 Hz corner (-3 dB) frequency, or approximately 8000 Samples/second. Exact reconstruction of the signal is guaranteed only if the signal being sampled is band-limited to 4000 Hz, the corresponding Nyquist band. However, by inspecting the specifications of channel class 1000, it is clear that signals above the Nyquist rate of 4000 Hz are attenuated only by a minimum of 12 dB. Such attenuation is not sufficient to remove the aliasing frequencies, i.e., those above 4000 Hz. To increase the attenuation above the Nyquist frequency, either the sampling rate must be increased, or else the pre-sample filter should have steeper rolloff. Therefore, HSRI proposes the following guideline:

PROPOSAL #3	SAMPLING RATES AND PRE-SAMPLE ANALOG FILTERS SHOULD BE SUCH THAT THE MINIMUM ATTENUATION AT THE NYQUIST RATE IS 24 dB.

DIGITAL FILTERING

The second inadequacy of current data processing guidelines is in the specification of dynamic response of digital filters. Unless the digital filter being used is an approximation of analog one, these guidelines cannot be intelligently applied and, more importantly, can easily be exceeded by "purely" digital filters.

Digital filters which approximate analog ones have transfer functions which may be written as closed-form expressions, and have an impulse response of infinite duration; hence, they are called Infinite Impulse Response (IIR) filters. More recently, digital filters which have a Finite Impulse Response (FIR) have been widely designed and implemented both in software and hardware. The advantage of these FIR filters is the linear phase characteristic of their dynamic response, which may be put to use to produce a phase-transparent filter.

A comparison of the FIR and IIR digital filters is outlined in Table 1. It is clear that the simplicity of the IIR filter does not offset the advantages of the FIR filter. Furthermore, optimum FIR filters can be economically designed and implemented.

Since FIR linear phase filters are inherently different from analog filters or their IIR counterparts, it is no longer feasible to specify the dynamic response in traditional terms, such as the corner (-3 dB) point or the attenuation rate (dB/octave). Instead, lowpass FIR linear phase digital filters must be specified as shown in Figure 1. A digital filter of this type is specified by four parameters:

1. The cutoff frequency (F_p) or pass frequency which defines the passband (0 dB gain),

2. The tolerance ($\pm\delta_1$, dB) or ripple allowed in the passband,

3. The attenuation (negative gain, $-\delta_2$ dB) of the stopband, and

4. The width of the transition band (ΔF) over which the gain drops from 0 dB at F_p (upper edge of the passband) to $-\delta_2$ dB at F_s (lower edge of the stopband $F_s = F_p + \Delta F$).

Based on its experience in the design and implementation of digital filters, HSRI proposes the following guidelines, and feels

COMPARISON BETWEEN TWO TYPES OF DIGITAL FILTERS

F I R (FINITE IMPULSE)	I I R (INFINITE IMPULSE)
• POLYNOMIAL DESIGN	• CLOSED-FORM DESIGN
• DIGITAL THEORY	• APPROXIMATELY ANALOG
• LINEAR PHASE	• NONLINEAR PHASE
• EXCELLENT MAGNITUDE	• EXCELLENT MAGNITUDE
• SPECS DIFFERENT: TRANSITION WIDTH, STOPBAND GAIN	• SPECS SAME AS ANALOG: - 3 dB POINT ROLLOFF (dB/OCTAVE)
• CORNER: SHARP	• CORNER: NOT AS SHARP
• FFT IMPLEMENTATION	• IMPLEMENTATION: ?
• EXACTLY PHASELESS	• DISTORTION OF PHASE

TABLE 1. COMPARISON OF TWO TYPES OF DIGITAL FILTERS

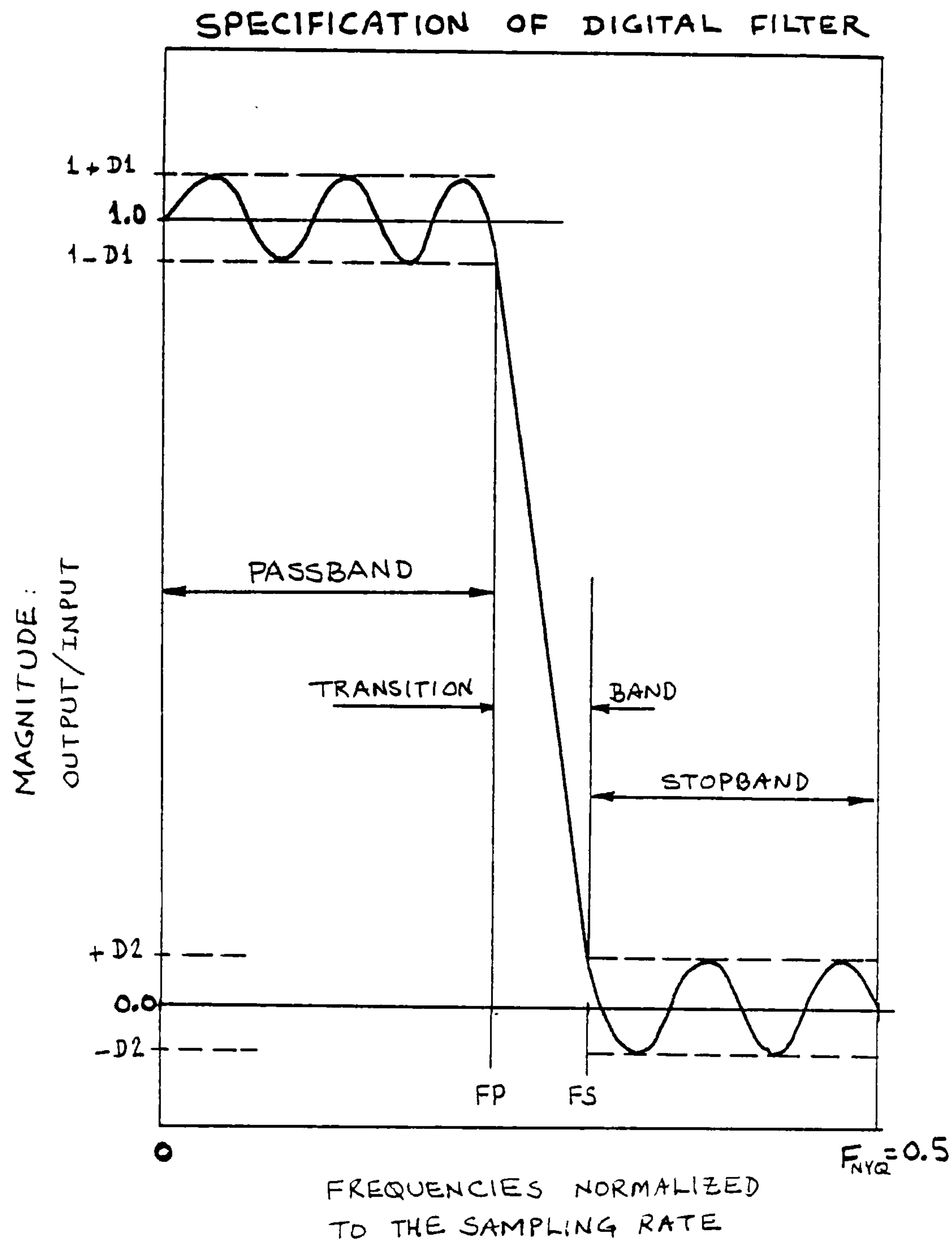

FIGURE 1. SPECIFICATION OF FIR LOWPASS FILTER

that they are feasible:

<table>
<tr><td>PROPOSAL

#4</td><td>USE LINEAR PHASE ANALOG & DIGITAL FILTERS AND SPECIFY DIGITAL FILTERS BY:

• PASSBAND RIPPLE NOT EXCEEDING 0.1 dB
• STOPBAND ATTENUATION AT LEAST 80 dB
• TRANSITION WIDTH: FUNCTION OF CUTOFF
LOW CUTOFFS ... WIDTH = 1.0 ×CUTOFF
HIGH CUTOFFS ... WIDTH = 0.25 ×CUTOFF</td></tr>
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CONCLUSIONS

Current practices in biomechanics instrumentation either do not exist or are inadequate. The proposals presented above are based on HSRI's own experience with such instrumentation and are limited to those areas which deserve immediate attention. It is hoped that these guidelines will be adopted and that a more complete set of guidelines will be recommended to cover the wide variety of instrumentations in biomechanics research.